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Advances in YBCO coated conductor technology

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Abstract

Processes for producing both the YSZ template film by IBAD and the YBCO superconducting film by PLD at 1 m lengths have achieved I_c values of 122 A and J_c values of 1 MA/cm^2. Improvements have been made in all stages of the process. Variations of I_c along the length of the 1-m samples stimulated development of a new in-field I_c measurement capability. The use of MgO as an IBAD template film has made great progress and can potentially decrease the time to produce the template film by more than an order of magnitude. A combination of electrical and microstructural investigations are being made to understand and improve the properties of the YBCO coated conductors.

1. Introduction

YBa2Cu3Ox (YBCO) can be deposited epitaxially onto single-crystal substrates to form a biaxially textured, i.e., both c-axis and in-plane textured, high critical current density (Jc) film. However, to use YBCO as a conductor, a method was needed to deposit YBCO onto a polycrystalline, flexible, base-metal substrate and yet to achieve a very high degree of alignment. This was first achieved by Iijima et al. [1], and almost simultaneously by Reade et al. [2]. The key is to provide a single crystal-like template film upon which the YBCO can grow epitaxially. The technique used here is known as ion beam assisted deposition (IBAD) in which, during deposition of an yttrium-stabilized zirconia (YSZ) film, an assisting ion beam is directed at an angle (~56°) to the substrate surface. The assist beam sputters away atoms in the YSZ film that are not in a particular crystallographic orientation, with the result that the YSZ film forms with a high degree of biaxial texture. The YBCO is then deposited directly on the YSZ or upon some intermediate layer, such as CeO2, to obtain better lattice matching.

Several other techniques have also been developed to achieve a template for YBCO film growth, such as inclined substrate [3] and shaped electrode [4] (both to produce a YSZ template film), and thermomechanical processing of a cubic metallic substrate to texture the substrate so that it may function as the template. [5]

The process used at Los Alamos National Laboratory is IBAD for the YSZ template layer, followed by pulsed laser deposition (PLD) for production of subsequent buffer layers and the YBCO film. The standard long sample size at Los Alamos has been 1-cm wide by ~1.1-m long since early 1997. We are investigating many facets of the process, from substrate material, through alternative IBAD template layers, to increasing the homogeneity and overall level of critical current in the YBCO layer. Several of these topics will be addressed below.

2. Experimental

Substrates are commercial Ni alloy Inconel 625 or Hastelloy C-276, 25~100-μm thick and 1-cm wide. A 115-cm length is spot welded into a loop. The substrates have an as-received surface finish R_a of 100-300 nm, which can be reduced to 2-5 nm by mechanical polishing. The tape is then cleaned and mounted in the IBAD chamber.

The standard apparatus for producing YSZ template films by IBAD employs a 5 cm diameter sputter ion gun (550 eV) and a 23 cm x 2.5 cm assist ion gun (~250 eV) to produce template films on one or two substrate loops mounted on a tape drive [6]. A moveable Faraday cup monitors the ion current and a fixed quartz crystal monitor monitors the vapor deposition. The two beam currents are adjusted such that the ion current to film deposition rate is approximately constant at

300 μA/cm^2/(0.5 Å/s). Shields are used to restrict vapor deposition to the region within the ion assist zone. The tapes rotate at 0.6 Hz, and for the ~16 hours required to achieve 0.5 μm of YSZ, the tape passes through the deposition zone many times resulting in a relatively uniform in-plane texture. YSZ (111) ϕ-scan minimum peak widths have been reduced by reducing the divergence of the assist ion gun and by optimizing the gun parameters.

In the last two years, MgO has also been used as a template film. [7, 8] Rather than showing gradually sharper in-plane texture as the template film thickness increases as in YSZ, MgO achieves biaxial alignment by a different mechanism at the film nucleation stage. Only about 10 nm of MgO is required, rather than the 500 nm or more for YSZ, to achieve a suitable template film for subsequent YBCO deposition. The MgO is grown on a buffer layer of amorphous Si_3N_4 on the substrate and a somewhat different sequence of buffer layers before the YBCO deposition.

The YBCO and any intermediate buffer layer deposition after the IBAD step are done in a separate chamber. [9] Short (<5 cm) samples are made with the substrate attached directly to a heater. The PLD system for the 115-cm long tapes uses a loop system with two rollers, with one of them serving as the tape heater. The 6.3-cm diam nickel disk contains a coaxial heater and a thermocouple for monitor and control of the temperature. At the deposition pressure of 0.2 Torr oxygen and sample temperature of 790°C, the tape temperature is about 50°C below that of the roller. This roller is driven through an external stepper motor and a worm gear. At a speed of 2.5 cm/min, a 1 μm thick YBCO film can be deposited at relatively low laser power. The full length tape requires about 40 minutes for coating.

After the leaving the deposition zone, the tape rapidly cools to room temperature. The next step is the deposition of 1-2 μm of silver by magnetron sputtering to protect the YBCO film and to allow attachment of electrical contacts. The final tape is then annealed in flowing oxygen at 550°C for 30 minutes to lower the contact resistance between the Ag layer and the YBCO film and to obtain the orthorhombic (superconducting) phase and fully oxygenate the YBCO.

Critical currents (I_c) were determined using standard 4-probe, dc transport techniques on the full width of the tape immersed in liquid nitrogen. The critical current is measured from end to end and then at 1 cm intervals along the tape length to check the homogeneity. For tapes with high I_c values (~100 A) and relatively large (>20%) variation in I_c as a function of position, it is possible to far exceed the I_c of a low I_c segment while measuring a high I_c segment, thus locally generating very large voltages and sufficient heat to damage the tape. For this reason, a translating stage with a set of permanent magnets generating a magnetic field of 0.6 T perpendicular to the tape was developed. The field reduces the I_c locally over the 1-cm gauge length being tested thus reducing the maxium end-to-end current needed for fully characterizing the tape and eliminating damage from local heating in those areas with lower I_c (0 T) values.

3. Results and discussion

Major progress was made in the past year in improving the in-plane orientation of the IBAD YSZ template film. The critical current across grain boundaries of the YBCO improves rapidly with increasing in-plane orientation, so it is very advantageous to improve this quantity. The Ar ions tend to diverge as they travel from the assist ion gun to the substrate. This divergence results in different grain orientation of the YSZ grains as a function of position along the long axis of the ion gun. The full width at half maximum (FWHM) of the Φ scan for the YSZ (111) x-ray peak was initially 25°. Polishing the tapes, resulting in a smoother surface, decreased this value by 4°. The first modification to the IBAD chamber was to install shielding near the assist ion gun to reduce the divergence of the beam at its edges. This resulted in another decrease in the FWHM of about 4°. The final step, resulting in a FWHM of ~12°, was obtained by careful tuning of the assist gun operating conditions. Table 1 lists the results achieved in this sequence of steps, all of which contribute to the final result. This allowed for major improvements in the

Table 1. IBAD YSZ template film texture results

Coating Condition	Tape Length	YSZ Φ FWHM
Stationary mode	25 cm	12°
Continuous mode - no shielding	1.1 m	25°
Continuous mode - no shielding - polished tape	1.1 m	21°
Continuous mode - with shielding	1.1 m	17°
Continuous mode - with shielding & assist gun modifications	1.1 m	12.5°

Table 2. Texture and superconductor properties for YBCO films on IBAD MgO

Substrate	R_{rms} (nm)	YBCO ϕ FWHM (°)	Thick-ness (μm)	J_c (75 K, SF) MA/cm^2
YSZ	0.36	2.1	0.46	3.1
Hastelloy C-276	Orb. Polish 3	3.6	0.22	3.9
Hastelloy C-276	Lin. Polish 2‖ 5⊥	4.0	1.0	0.86
Hastelloy C-276	Lin. Polish 2‖ 5⊥	6.1	1.3	0.73

superconducting performance of the YBCO because of the very strong dependence of the critical current density on the in-plane orientation.

The development of the alternative MgO template film has the major advantage over YSZ in that very good in-plane orientation occurs on nucleation in the former. This is illustrated in Fig. 1. Because film thickness is roughly equivalent to time, it is clear that the use of MgO as a template film can significantly speed up this process, which is the rate limiting step in production of YBCO coated conductors.

Initial work on MgO used single-crystal substrates. This was soon extended to Ni-Cr polycrystalline substrates. [8] Monitoring of the electron diffraction pattern during deposition of the MgO is critical to obtaining the best in-plane texture. This complicates the deposition process compared to that for YSZ. At this time, deposition of MgO template films has been done on stationary substrates only. Some recent results are collected in Table 2. Already, short-sample results with

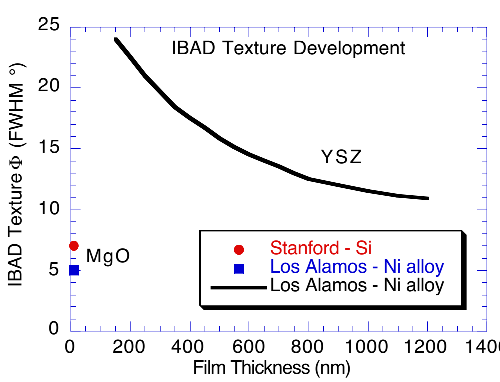

Fig. 1. Development of in-plane texture during the IBAD process. A Si substrate was used in the work at Stanford. [7]

critical-current density (J_c) values near 1 MA/cm^2 for 1-μm thick films have been achieved.

Improvements in long-length superconductor performance of YBCO coated conductors have been taking place over the last several years. [9] Figure 2 shows this progress as a function of tape length and time. Many factors go into this enhanced performance; these include those related to substrate preparation, polishing, and cleaning; the improvements discussed above to the IBAD process; more careful monitoring and control of the substrate temperature during YBCO deposition; and changes to the Ag overcoating and oxygen annealing process.

Along with increasing end-to-end I_c values, the variation in I_c along some of the best tapes was decreased from 44 A ± 45% in 1998 to 96 A ± 20% in 1999. Nevertheless the source of this spatial variation is a subject of intense investigation. Correlation of low I_c regions, deduced with the position dependent, in-field I_c probe, with the YBCO, buffer layer,

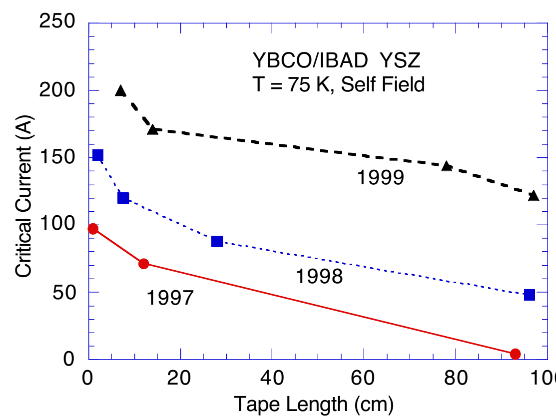

Fig. 2. Champion critical-current values as a function of tape length (end to end values) for 1-cm wide YBCO coated conductors.

template film, and substrate microstructures is an important step in improving conductor performance. Transmission electron microscopy (TEM), scanning electron microscopy, and optical microscopy have been used to investigate various features of the tape microstructure, such as high-angle grain boundaries, growth morphology, interfacial reactions, and other features that may have an impact on YBCO performance. As an example, the TEM image in Fig. 3 shows a long transverse section of a high quality tape with an yttria buffer layer on the YSZ template film. Some of the yttrium in the Y_2O_3 reacts with YBCO to form a continuous reaction layer of Y_2BaCuO_5 (Y-211). Porosity at the YBCO/reaction layer interface and defect growth of these reaction products into the YBCO is sometimes observed even in high quality films with this and other buffer layer architectures. Plan view TEM images show both well connected and less well connected paths for current flow in YBCO coated conductors. [10] The results of these investigations will be used to feed back to and optimize the processes for producing high critical current YBCO.

4. Summary

Processes for producing both the YSZ template film by IBAD and the YBCO superconducting film by PLD at 1 m lengths have achieved I_c values of 122 A and J_c values of 1 MA/cm^2. Improvements have been made in the substrate surface finish, in the in-plane orientation of the IBAD YSZ template film, and in buffer layer and YBCO properties. Variations of I_c along the length of the 1-m samples stimulated development of a new in-field I_c measurement capability to determine that variation nondestructively. The use of MgO as an IBAD template film has made great progress and can potentially decrease the time to produce the template film by more than an order of magnitude. A combination of electrical and microstructural investigations are being made to understand and improve the properties of the YBCO coated conductors.

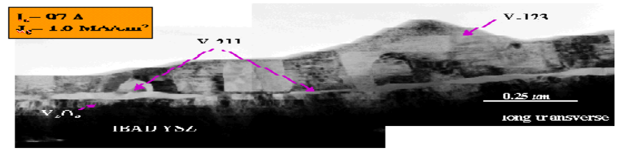

Fig. 3. TEM transverse section of a YBCO coated conductor illustrating an interlayer reaction product of Y-211.

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